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Low-grade heat conversion into power using organic Rankine cycles – A review of various applications

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ABSTRACT

An organic Rankine cycle (ORC) machine is similar to a conventional steam cycle energy conversion system, but uses an organic fluid such as refrigerants and hydrocarbons instead of water. In recent years, research was intensified on this device as it is being progressively adopted as premier technology to convert low-temperature heat resources into power. Available heat resources are: solar energy, geothermal energy, biomass products, surface seawater, and waste heat from various thermal processes. This paper presents existing applications and analyzes their maturity. Binary geothermal and binary biomass CHP are already mature. Provided the interest to recover waste heat rejected by thermal devices and industrial processes continue to grow, and favorable legislative conditions are adopted, waste heat recovery organic Rankine cycle systems in the near future will experience a rapid growth. Solar modular power plants are being intensely investigated at smaller scale for cogeneration applications in buildings but larger plants are also expected in tropical or Sahel regions with constant and low solar radiation intensity. OTEC power plants operating mainly on offshore installations at very low temperature have been advertised as total resource systems and interest on this technology is growing in large isolated islands.

Contents

1. Introduction

The steam Rankine cycle is one of the most important ways to transform on large scale thermal energy into power. Examples are nuclear and coal-fired power plants. Main components of a steam power cycle are: condenser, pump, vaporizer, turbine and the working fluid. In this cycle, water used as working fluid has following thermodynamic characteristics:

- molecular weight: 18 kg/kmol
- boiling point: 373.15 K–101.325 kPa
- freezing point: 273.15 K–101.325 kPa
- triple point: 273.16 K–0.611 kPa
- critical point: 647 K–22.06 MPa
- latent heat: 2256.6 kJ/kg–101.325 kPa
- specific heat: 4.18 kJ/kg K

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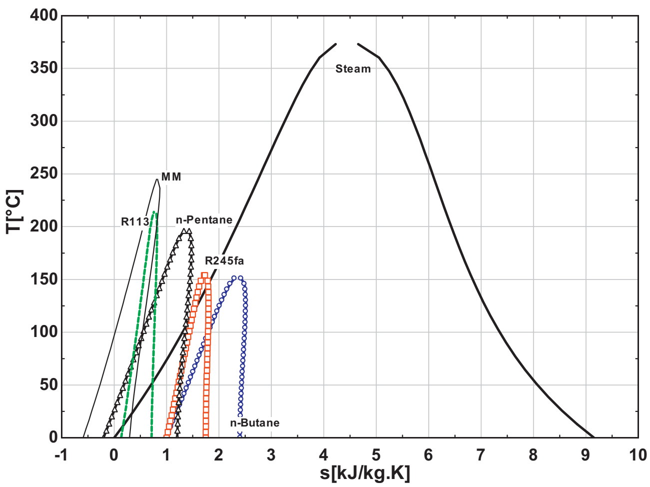

Fig. 1. *T–s* diagrams of water and few organic fluids.

Its *T–s* diagram in the form of a bell that characterizes wet fluids is depicted in Fig. 1. Advantages presented by water as working fluid are [1]:

- very good thermal/chemical stability (no risk of decomposition)
- very low viscosity (less pumping work required)
- good energy carrier (high latent and specific heat)
- non-toxic, non-flammable and no threat to the environment (zero ODP, zero GWP)
- cheap and abundant (present almost everywhere on earth)

However, many problems are encountered when using water as working fluid [2]:

- need of superheating to prevent condensation during expansion
- risk of erosion of turbine blades
- excess pressure in the evaporator
- complex and expensive turbines

Because of the aforementioned reasons, water is more suitable for high temperature applications and large centralized systems.

Seeking for small and medium scale power plants, the problems encountered with water can be partially mitigated by selecting an appropriate fluid. Organic compounds characterized by higher molecular mass and lower ebullition/critical temperature than water have been proposed in so called "Organic Rankine Cycles". An Organic Rankine Cycle (ORC) has several advantages over conventional steam power plant:

- Less heat is needed during the evaporation process.
- The evaporation process takes place at lower pressure and temperature.
- The expansion process ends in the vapor region and hence the superheating is not required and the risk of blades erosion is avoided.
- The smaller temperature difference between evaporation and condensation also means that the pressure drop/ratio will be much smaller and thus simple single stage turbines can be used.

Comparison of fluids properties in steam and organic Rankine cycles is summarized is Table 1. Potential substances identified for ORCs are [3–10]:

- Hydrocarbons (HC)
- Hydrofluorocarbons (HFC)

Table 1
Summary of fluids properties comparison in steam and organic Rankine cycles.

	Steam cycle	Organic Rankine cycle
Fluid	Water	Organic compound
Critical pressure	High	Low
Critical temperature	High	Low
Boiling point	High	Low
Condensing pressure	Low	Acceptable
Specific heat	High	Low
Viscosity	Low	Relatively high
Flammability	No	Yes, and depends on fluid
Toxicity	No	Yes
Environmental impact	No	High and depends on fluid
Availability	Available	Supply problem
Cost	Cheap	Expensive

- Hydrochlorofluorocarbons (HCFC)
- Chlorofluorocarbons (CFC)
- Perfluorocarbons (PFC)
- Siloxanes
- Alcohols
- Aldehydes
- Ethers
- Hydrofluoroethers (HFE)
- Amines
- Fluids mixtures (zeotropic and azeotropic)
- Inorganic fluids

A working fluid in organic Rankine cycle machine plays a key role – It determines the performance and the economics of the plant [11]. This justifies the abundant literature dedicated to fluids selection for very different heat recovery applications from which characteristics of good fluids can be extracted [3,4,9,12–15]:

- Vapor saturation curve with zero or positive slope (ds/dT) (isentropic or dry fluids)
- High latent heat of vaporization
- High density (liquid/vapor phase)
- High specific heat
- Moderate critical parameters (temperature, pressure)
- Acceptable condensing and evaporating pressures (>1 bar and <25 bar resp.)
- Good heat transfer properties (low viscosity, high thermal conductivity)
- Good thermal and chemical stability (stable at high temperature)
- Good compatibility with materials (non-corrosive)
- High thermodynamic performance (high energetic/exergetic efficiency)
- Good safety characteristics (non-toxic and non-flammable)
- Low environmental impacts (low ODP, low GWP)
- Low cost and good availability

Although investigated since the 1880s, organic Rankine cycles have never been popular until today's growing concern over the future depletion of fossil fuels and the global environmental destruction is turning the interest on low grade energy recovery systems. Owing to its low operating temperature, an organic Rankine cycle can suitably recover heat from various sources: solar energy, geothermal heat, biomass, industrial waste heat, etc. – and this has already been demonstrated as can testify numerous plants installed in USA, Canada, Italy, Austria, Germany, Netherlands, Sweden and elsewhere [16–18]. The number of ORC plants installed worldwide is steadily increasing but not at the same rate for all applications. Growing number of ORC manufacturers and installers propose machines easily adaptable to existing heat sources for on-site power generation at different power sizes [19]. Although these companies keep record of their references, there is a lack of exact

statistics to determine the share of each application. Authors in the present paper report and analyze different organic Rankine cycle applications with respect to the nature of the heat source and technology maturity.

2. Organic Rankine cycle applications

2.1. Binary geothermal power plants

The Earth is increasingly warmer the deeper one goes. This underground energy emitted from the center of the earth and usually called geothermal energy can be used for heating processes and/or electricity generation. The Earth's heat flow – i.e. the amount of heat released into space from the interior through a unit area in a unit of time, varies from place to place on the surface and with the time at a particular location. The Earth's total output is estimated at about 4×10^{13} W, which is more than threefold the world total energy consumption [20]. The average geothermal gradient near the Earth's surface is about 300 K/km and is not equally distributed, allowing some locations to be more suitable for geothermal applications than others.

First use of geothermal energy for electricity generation started in Italy with experimental work by Prince Ginori Conti in 1904–1905. And first commercial plant of 250 kWe is reported to have been erected in 1913 at Larderello, Italy [21]. Currently, there are 504 geothermal power plants in operation in 27 countries with a total installed capacity of about 10 GW [22]. Major types of geothermal power plants are [22,23]: dry steam, single-flash, double-flash and binary-cycle plants. Comparison between available options is summarized in Table 2. Flash systems are used for moderate and liquid-dominated resources, dry steam plants for dry-steam resources and binary cycles are well adapted for low-temperature liquid-dominated resources.

In the geothermal binary plant depicted in Fig. 2, the thermal energy of the geothermal fluid is transferred to a secondary working fluid via heat exchangers for use in a conventional Rankine cycle. The organic working fluid receives heat, evaporates and expands in the turbine before being condensed and returned back to the evaporator by the feed pump. Cooling of the condenser is assured by air coolers, surface water cooling systems, wet-type cooling towers or dry-type cooling towers. The first binary geothermal plant was put into operation at Paratunka, Russia in 1967 [21,24]. It was rated at 680 kWe using water at a temperature of 81 °C and this plant proved the feasibility of the binary concept. For low-temperature geothermal fluids below 150 °C, it is difficult to implement cost effective flash steam plants and the binary option is the sole solution. Today, binary power plants are the most widely used type of geothermal power plant with 162 units, generating 373 MW of power. They constitute 32.14% of all geothermal units in operation but generate only 4% of the total power [22]. Few of these plants are given in Table 3. The technology has been developed and commercialized since the 1980s by Ormat Technology Inc. [25,26]. In the MW power range, ORC modules incorporate conventional turbines and are cost-effective, while at lower power outputs the lack of cheap turbines renders the technology hardly applicable. Brasz et al. [27] suggested to use HVAC components. By applying this concept, they turned a standard 350 ton air-conditioning system into a 200 kW ORC power plant. The product is commercialized under the brand name PureCycle®280 by United Technologies Corporation (UTC). Plants based on this technology are: East Hartford (CT), Austin (TX), Danville (IL) and Chena (Alaska) to quote just a few [27–29]. Similar developments have been carried out by Smith and Stosic at City University, UK [30–32] who successfully converted screw compressors into screw expanders. Electratherm [33] and BEP Europe [34] are companies commercializing screw expanders based ORCs.

In geothermal plants, the constant preoccupation is the optimal resource utilization. This is measured in terms of energy and exergy efficiencies. First law efficiencies are found in the range 5–15% while second law efficiencies are typically in the range 20–54% [35,36]. A large number of studies define criteria and guidelines for the optimal design of binary cycle power plants. According to Borsukiewicz-Gozdur and Nowak [37], geothermal water mass flow should be appropriately chosen for power maximization. Kanoglu and Bolatturk [38] assessed the thermodynamic performance of the Reno (Nevada, USA) binary plant. This plant uses geothermal fluid at 158 °C and isobutane as working fluid. Exergy and energy efficiency obtained were 21% and 10.20%, respectively. The brine re-injected at relatively high temperature (90 °C), accounts for 35.3% of exergy losses and 55.7% of energy losses and could be used for district heating to increase the overall efficiency of the plant. Numerous studies are dedicated to the selection of adequate fluids using very different optimum criteria [10,36,39–46]. Heberle and Brüggermann [39] compared second law efficiencies of organic Rankine cycle in series and parallel circuits. Gawlik and Hassani [40] used the levelized electricity cost (LEC) to select among isobutane and propane based mixtures, in addition to pure fluids which ones were suitable for resources in the range 129.44–190.55 °C. Madhawa Hettiarachchi et al. [41] used the ratio of the total heat exchanger area to net power output as an objective function and implemented the steepest descent method for function minimization. Other authors choose a set of criteria during their investigation. Screening criteria used by Guo et al. [46] include net power output per mass flow rate, the ratio of total heat transfer area to net power output and electricity production cost (epc). Shengjun et al. [45] conducted similar study, where they added two more indicators: thermal and exergy efficiencies. Till now, No single criterion has been found as most important for optimal design – optimized fluids always vary with the objective function and the plant optimum operating parameters as well. Although, theoretical studies point out that fluids mixtures owing to their temperature glide during the evaporation process have the advantage of reducing the system exergy destruction, and increase the plant efficiency through better matching with the heat source and cold sink profiles, no installation to our knowledge operates at the moment on this concept. The thermal/chemical stability or the variations of the components fractions during cycle operation require investigations. Transcritical cycles were investigated [45,47–49] as way of increasing the cycle performance but this con-

Table 2
Comparison of different types of geothermal plants [22].

Type	Resource temperature (°C)	Utilization efficiency (%)	Plant cost and complexity
Double-flash	240–320	35–45	Moderate ▸high
Dry-steam	180–300	50–65	Low-moderate
Single-flash	200–260	30–35	Moderate
Basic binary	125–165	25–45	Moderate ▸high

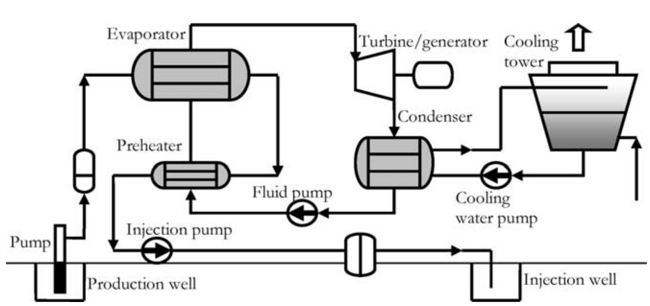

Fig. 2. Flow diagram for a binary geothermal power plant.

Table 3
Few binary ORC geothermal power plants.

Plants/location	Resource temp. (°C)	Resource mass flow	Working fluid	Gross/net power (MW)	Thermal efficiency (%)
Amedee, USA	104	205 l/s	R-114	2.0/1.5	–
Wineagle, USA	110	63 l/s	Isobutane	0.75/0.6	–
Altheim, Austria	106	86 l/s	–	–/1.0	–
Otake, Japan	130	14.661 kg/s	Isobutane	–/1.0	12.9
Nigorikawa, Japan	140	50 kg/s	R-114	–/1.0	9.81
Reno, NV, USA	158	556 kg/s	Isobutane	27/21.744	10.2

cept has two major problems: (1) safety concerns due to excess pressures in the evaporator and (2) difficult condensation with fluids displaying very low condensing temperature.

2.2. Solar thermal power systems

2.2.1. Modular organic Rankine cycle solar systems

Several factors are increasing the market potential for small power plants: the need of distributed power systems in remote and isolated areas of developing countries, the need for sustainable power for economic growth in developing countries, the need of small and efficient polygeneration systems for grid connected applications in developed countries, the need to generate clean electricity through renewable energy sources, and the deregulation and privatization of the electrical generation sector worldwide. In binary geothermal power plants, geothermal fluid replaced by other heat transfer fluids: water, synthetic/mineral oil, and nitrate salts heated up to 400 °C in solar thermal collectors produce distributed modular solar power plants in the kW to MW range. Modular organic Rankine cycle solar power plants operate on the same principle as conventional parabolic trough systems but use an organic fluid instead of steam. Advantages of these systems are as follows [50]:

- Low temperature operation (<300 °C): heat transfer fluids such as Caloria, low temperature solar collectors, and low temperature ORC modules which can operate well in regions with low solar radiation intensity like sub-Sahara African regions.
- Modularity: large solar ORC plants of several MW power output can be built by combining on the same site a great number of ORC modules.
- Reduced capital and O&M costs: cheap materials can be used – inexpensive heat transfer fluid, cheap solar collectors, and relatively cheap ORC machines. Air-cooled condensers save water resources, and remote operation reduces the number of operators.

Conventional CSP technologies include: central receiver systems, parabolic trough (PTC), Integrated combined gas cycles (ICGC) and dish Stirling systems. Parabolic trough technology has demonstrated its ability to operate in a commercialized environment and several plants based on this technology were recently erected or are under construction [51]. It is considered at the moment as the most mature CSP technology but could face future competition from Linear Fresnel Reflectors [52]. Owing to recent progress in Solar Material Sciences, various types of efficient and relatively cheap solar thermal collectors operating in the low to medium temperature ranges have been made available on the market [53,54]. Table 4 gives the operating temperature and concentration ratio of different solar thermal collectors' technologies [55].

Small ORCs have been investigated since 1990s, but could not be widely implemented because of the lack of small and efficient expansion devices. Although various types of devices were investigated as potential expansion machine candidates, none emerged with good reliability and outstanding performances to bring cogeneration ORCs at commercial stage. Badr et al. [56,57] assessed several types of power-producing machines for low power generation including turbines (radial, impulse, reaction, and multistage) and positive displacement units (screw, piston, and vane expanders and Wankel engines) from which screw and Wankel-type expanders showed good prospects. In low power range (<1 MW), turbines are not suitable because of their lower efficiency and higher manufacturing cost whereas it represents the technology of choice for large scale systems. Recalling desired characteristics of a good machine, it should be highly reliable and highly efficient throughout wide ranges of operating conditions, possess very few moving parts, display low vibration and noise levels, and be inexpensive. Kane [58], Lemort [59], Quoilin et al. [60] and Smith et al. [31] are among authors who suggested scroll and screw expanders in regard to the performances achieved – global isentropic efficiency up to 70% [30,56,59,61–63]. Other aspects: system design and optimization [64–68], system dynamics and controls [69], solar collectors and working fluids selection [13,70–72], and experimental research [73–78] of solar modular power plants have been subject to intense activities last few years. In an attempt to show variety of research carried out, few of successful works are quoted in up-coming lines.

Nguyen et al. [78] built and tested a prototype of low temperature ORC system. It used n-Pentane as working fluid, and encompassed: a 60 kW propane boiler, compact brazed heat exchangers, a compressed air diaphragm pump, and a radial flow turbine (65,000 rpm) coupled to a high speed alternator (Fig. 3). With hot water inlet temperature: 93 °C, evaporating temperature: 81 °C, condensing temperature: 38 °C and a working fluid mass flow rate of 0.10 kg/s, the power output obtained was 1.44 kWe and the efficiency 4.3%. The cost of the unit was estimated at £21,560. The turbine-generator accounted for more than 37% of the system cost. Authors concluded that the system could be cost-effective in remote areas were good solar radiation is available provided the efficiency of the expander is improved (>50%) and the unit produced in mass.

Medium temperature collectors coupled with ORC modules could efficiently work in cogeneration application producing hot

Table 4
Typical temperature and concentration range of the various solar thermal collector technologies.

Technology	T [°C]	Concentration ratio	Tracking
Air collector	0–50	1	–
Pool collector	0–50	1	–
Reflector collector	50–90	–	–
Solar pond	70–90	1	–
Solar chimney	20–80	1	–
Flat plate collector	30–100	1	–
Advanced Flat Plate collector	80–150	1	–
Combined heat and power solar collector (CHAPS)	80–150	8–80	One-axis
Evacuated tube collector	90–200	1	–
Compound Parabolic CPC	70–240	1–5	–
Fresnel reflector technology	100–400	8–80	One-axis
Parabolic trough	70–400	8–80	One-axis
Heliostat field + Central receiver	500–800	600–1000	Two-axis
Dish concentrators	500–1200	800–8000	Two-axis

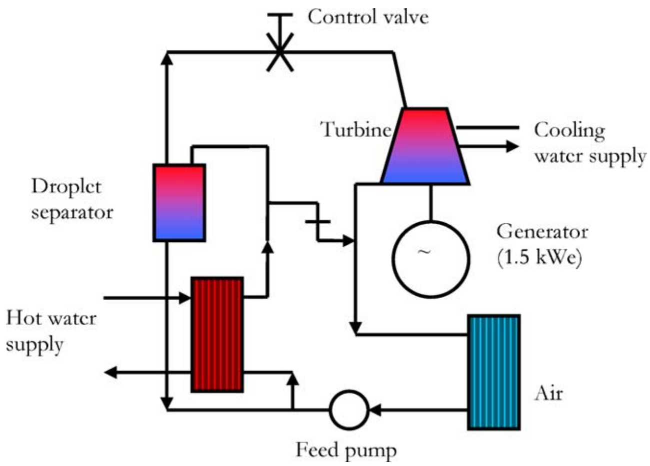

Fig. 3. A micro-organic Rankine power system [78].

water and clean electricity. On-site tests carried out in Lesotho (Fig. 4) by Solar Turbine Group International prove that micro-solar ORC based on HVAC components is cost-effective in off-grid areas of developing countries where billions of people continue to live without access to electricity [64,79,80]. Another system which integrates scroll expander and steam accumulator was reported by Saitoh et al. [75]. Water in the latter system was used as the heat transfer fluid while R113 is the working medium. Laboratory tests performed with 200 liters of hot water stored in the accumulator and working fluid mass flow rate of 0.016 kg/s, gave expander efficiency of 63%, power output 450 W and Rankine cycle efficiency 12%. Autonomous operation tests at Sendai City, Japan, on a typical summer day: solar radiation – 890 W/m^2 and ambient temperature 30 °C gave as results: power output 350 W, ORC efficiency 11%, and system efficiency 7%.

Hybrid systems involving another energy source in addition to solar have been also considered [81,82]. Hybrid systems have nearly 100% availability and avoid the integration of bulky and expensive energy storage system. An example of hybrid solar/gas driven micro-combined heat and power (CHP) system was reported by Yagoub et al. [81]. A schematic of the system is shown in Fig. 5. This system uses 25 kW evacuated tube collectors and 25 kW gas condensing boiler. Two pairs of fluid/pump were tested: HFE-301/electric pump and n-Pentane/diaphragm pump. HFE-301 presented several advantages over n-Pentane (R601): higher efficiencies, lower temperature requirement, higher vapor dryness, and higher isentropic efficiency (85% versus 40%). An advanced concept of mini-hybrid solar/diesel power plant integrating solar concentrators, two superposed organic Rankine cycles and a diesel engine was proposed by Kane et al. [83]. Linear Fresnel collectors track the sun and concentrate the rays on the receiver tube in which pressurized water circulates. Superposed cycles use hermetic scroll expander/generators, and R123 and R134a as working fluids (Fig. 6). The diesel engine was integrated to guarantee a minimum level of both power and heat availability at night or during periods of low radiation. Laboratory and on-site tests carried out at Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland gave system efficiency of 7.74% in “solar only” mode and 41% in “fossil fuel only” mode.

A 1 MW solar ORC power plant owned by Arizona Public Service (APS) is in operation since 2006 at Red Rock in Arizona, USA [84]. LS-2 collectors provided by Solargenix are coupled to an ORMAT ORC module filled with n-Pentane. The ORC and solar to electricity efficiency are 20.7% and 12.1%, respectively. McMahan [69] proposed the cycle efficiency maximization (optimal heat exchanger area) as a way to reduce the plant capital cost (down to 17%). In 2009, a 2 MW CSP plant was inaugurated at the National Energy Laboratory of Hawai Authority (NELHA) in the Kona desert, Hawai, USA [85,86]. This project was funded and developed by Sopogy under the Hawai Clean Energy Initiative. Solar parabolic trough collectors were supplied by Alanod Aluminium-Veredlung and the ORC machines by ElectraTherm Inc. According to the project developer the ultimate goal is to reach 30 MW by 2015. Considering the development of cheap and efficient solar concentrating collectors and reliable and cost effective ORC modules, more medium scale solar CSP plants are to be expected in the near future.

2.2.2. Solar pond power systems

A solar pond power plant (SPPP) is made of two subsystems: a salt gradient solar pond and a conventional Organic Rankine Cycle. The salt gradient solar pond (SGSP) is a flat and uncovered large reservoir of water acting as a liquid solar thermal collector/heat store. It absorbs solar radiation (diffuse and direct), transforms it into heat and stores it in the form of hot water. A salt gradient solar pond is artificially divided into three zones [87]:

- The upper convective layer of thickness between 0.15 and 0.30 m with low salinity water acts as a transparent cover and thermal insulator.
- The bottom layer of thickness from 2 up to 7 m with high-concentration brine that acts as a heat absorber and heat store.
- The middle layer of thickness between 1 and 1.5 m acts as an additional insulator and is called the gradient salt layer. In this layer, salinity and temperature increase from the top to the bottom.

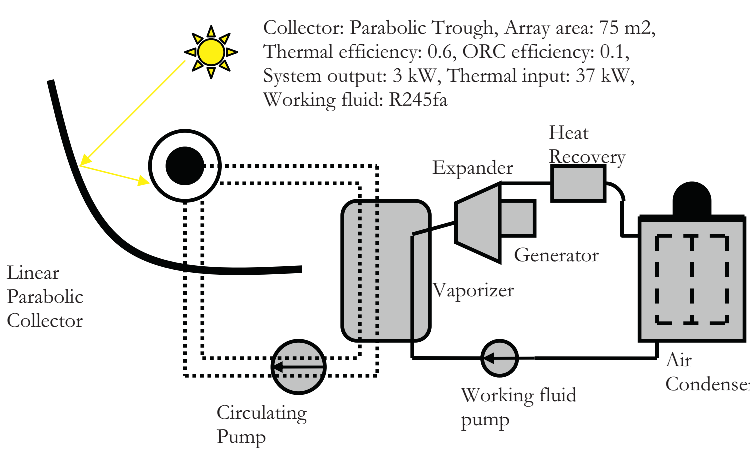

Fig. 4. Schematic of the solar ORC tested in Lesotho [79].

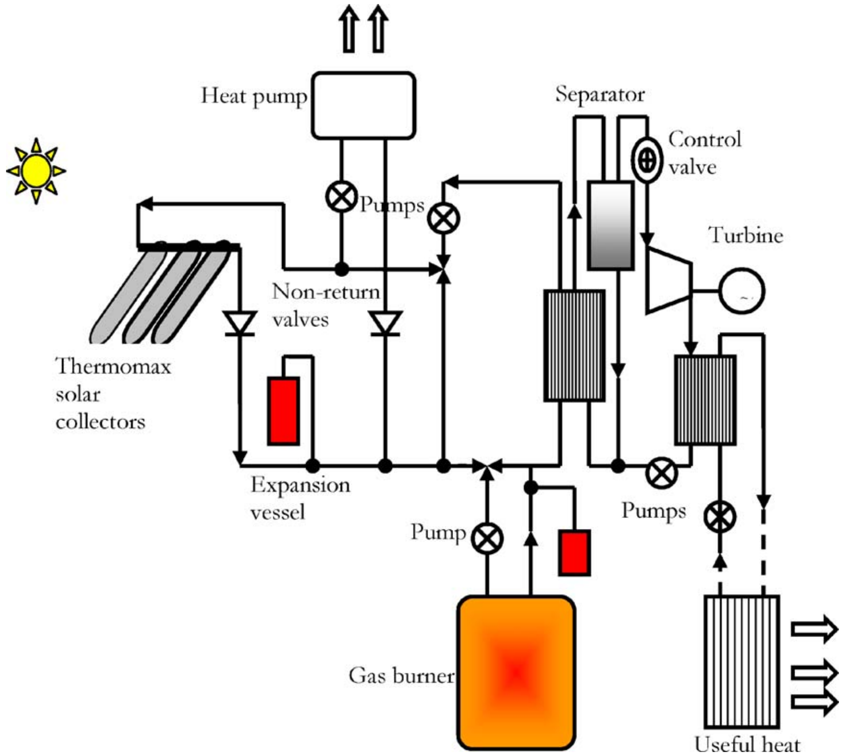

Fig. 5. Schematic of the hybrid solar-gas driven micro-CHP system [81].

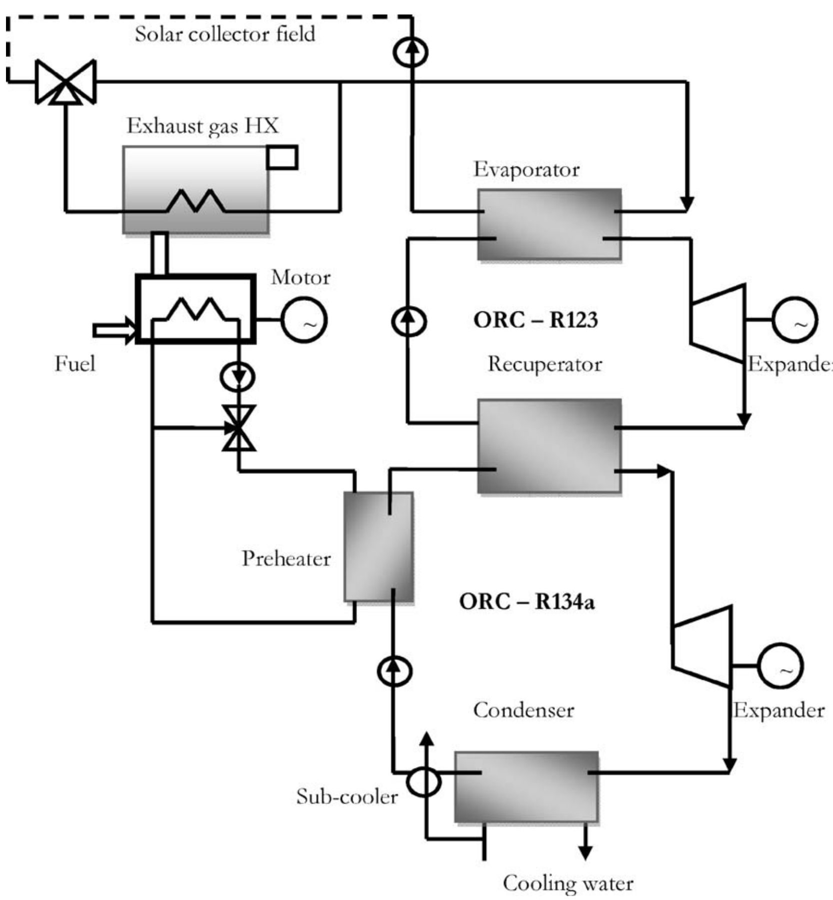

Fig. 6. Schematic of the SPS power unit [83].

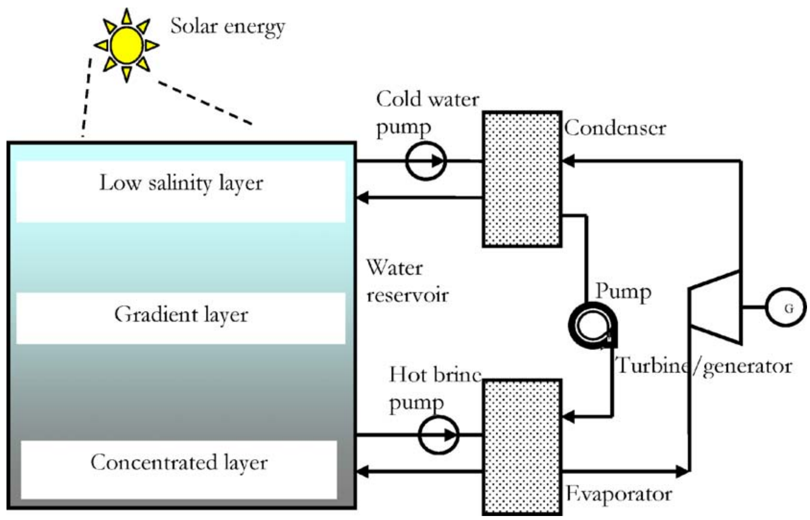

Fig. 7. Principle of a Solar pond power plant.

This phenomenon was discovered in 1902 by Kalecsinsky in a lake located near Szovata, Transyslvania [88]. The maximum temperature obtained in a pond is about 90–100 °C, making it suitable for Rankine Cycles working with low boiling point organic fluids such as R134a and Propane (R290). The configuration of the salt gradient solar pond matches the sources of an Organic Rankine Cycle. The upper layer serves as cold source to cool the condenser while the bottom layer supplies the evaporator with heat.

The principle of operation is simple; during the day, the pond is charged while the extraction of heat can be scheduled for precise period of time. During operation, the bottom layer supplies heat to the evaporator where it is used to evaporate the working fluid. The fluid at vapor state is expanded in the turbine and cooled in the condenser before being pumped to the evaporator to close the cycle. A solar pond power system is illustrated in Fig. 7. The thermal performance of a solar pond is around 15–25% while the solar-to-electric efficiency is about 0.8–2% [88]. Research on solar ponds started in Israel in 1950–1970 and the first solar pond with a surface area of 1100 m^2 was built in 1975 at the Dead Sea Works [87,88]. Since that period, several power plants based on this technology were constructed and operated at different sites around the world: 5 MW–250,000 m^2 SPPP at Beith Ha'avara, Israel; Ein Boqek, Israel (150 kW/6250 m^2); Yavne, Isreal (6 kW/1500 m^2); Alice Springs, Australia (15 kW/1600 m^2); El Paso, USA (70 kW/3350 m^2).

2.3. Solar ORC-RO desalination systems

Desalination consists of removing salt and other solids particles from raw water so called seawater or brackish water depending on the concentration of salts to make it suitable for human consumption. Desalination technologies are classified in two groups according to their separation mechanism: thermal and membrane based technologies [89]. Thermal desalination separates salt from water by evaporation and condensation, whereas in membrane desalination water diffuses through a membrane, while the salts are almost completely retained. Reverse osmosis (RO) and multi-stage flash (MSF) are the most widely used technologies. Recently, there has been a trend to couple desalination techniques with renewable energy in order to reduce the impact of conventional power plants on the environment. The aforementioned techniques can be coupled either with solar PV panels or solar thermal collectors. RO can be powered by electricity or mechanical power. Reverse osmosis is a pressure driven separation technique based on a property of certain polymers called semi-permeability. While they are very permeable for water, their permeability for dissolved substances is low. By applying a pressure difference across the membrane the water contained in the feed is forced to permeate through the membrane. In order to overcome the feed side osmotic pressure, fairly high feed pressure is required. Pressures applied in reverse osmosis applications vary from 15 to 25 bars for brackish water and 60–80 bars for seawater. Pumping process can be easily achieved through electricity or shaft power thus, making RO the most suitable candidate for renewable energy powered desalination system. A solar driven ORC-RO system couples a solar thermal engine and a RO desalination sub-system (Fig. 8). The solar thermal engine transforms the solar radiation into mechanical power. The useful shaft power by mechanical coupling drives the high pressure pump (HPP) of the RO unit.

Early research on solar thermal driven pumping systems involving the Rankine power cycle started in the second half of the 19th century with the works of Augustin Mouchot and Abel Pifre [90]. From that time till the end of the 20th century, the main application targeted was the small scale water pumping systems for irrigation of farms. Many systems operating on this scheme were built in many countries around the world as reported by Delgado-Torres [90] and Wong and Sumathy [91]. These systems used steam or organic compounds such as R11, R114 and R113 as working fluids. Solar driven irrigation systems are of special significance in countries where the economy relies on agricultural activities undertaken by poor farmers in remote areas far from electricity grid, and in a context of water scarcity and increasing oil prices. Since the 1980s, solar PV-water pumping systems favored by the decreasing cost of PV, modularity and less moving parts are being preferred to solar thermal pumping systems.

At the moment the global warming is being considered as a major threat to our life, solar thermal engines are suggested for powering RO-desalination units. Earliest plant is reported to have been constructed in Cadarache, France [92]. The high pressure pump was powered by a 2.5 kW solar heat engine with R114 as working fluid, and a fresh water production of 2.5 m^3/h from brackish water. Steam RC-RO systems have been studied by Voros et al. [93] and Bouzayani et al. [94]. These authors consider steam temperature of about 450 °C at the turbine inlet. The implementation of organic fluids with appropriate critical temperature such as Toluene, Siloxanes, Ammonia, Pentanes, etc. in medium and low temperature ORC-RO systems is possible. Recently, Bruno et al. [7] carried out technical and economic feasibility study of solar ORC-RO desalination technologies and concluded that solar ORC-RO is

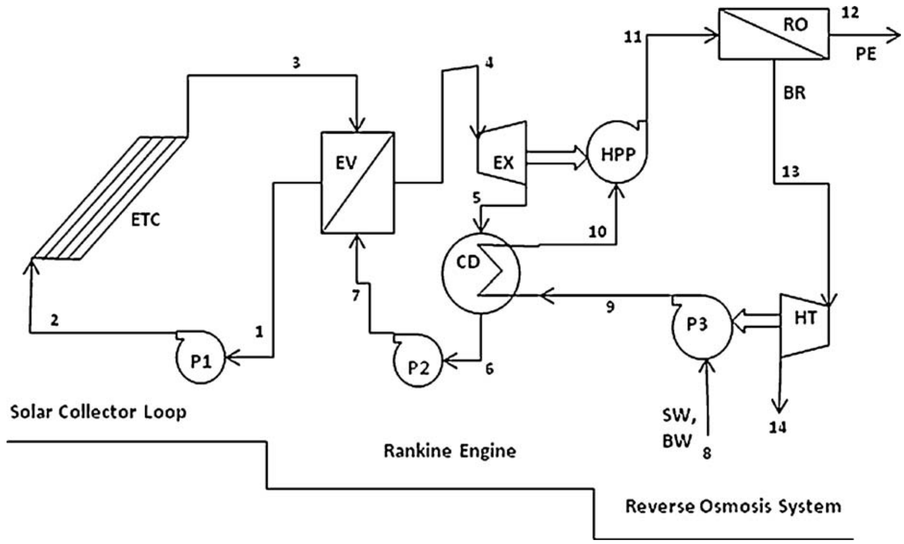

Fig. 8. Schematic of a Rankine driven reverse osmosis desalination system (ETC: solar thermal collectors; EV: evaporator; EX: expander; HPP: high pressure pump; P1, P2, P3: pumps, HT: hydraulic turbine; CD: condenser; RO: membrane modules; BR: brine; PE: permeate; SW: seawater; BW: brackish water).

a cost-effective option in comparison to PV-RO. Parabolic trough collectors in single or double cascade ORC with Toluene, Pentanes or Propylbenzene as working fluids could form the baseline technology for large and medium size solar ORC-RO systems. Cycles operating with maximum temperature of 250–400 °C and 35 °C condensing temperature yield a cycle efficiency of about 25–35%. Under this condition, a 15 m^3/day plant could produce water at about 2.30 €/m^3 from brackish water or 5 €/m^3 from seawater.

Solar ORC-RO could be scaled down using well known HVAC components. In this perspective, Manolakos et al. [95,96] designed and tested a small stand-alone system using a scroll expander, evacuated tube solar collectors and R134a as working medium. Economic comparison [97] showed the basic Rankine Cycle configuration was not cost effective compared to PV-RO systems of similar size. Cost comparison study in case of seawater for Thirasia Island, Greece gave cost figures of 7.77 €/m^3 for PV-RO and 12.53 €/m^3 for ORC-RO. In sake of optimal use of solar collectors, Kosmadakis et al. [98] suggested a dual organic Rankine cycle system.

2.4. Duplex-Rankine cooling system

Solar assisted air-conditioning systems with the advantages they have to reduce the summer electricity peak load and energy consumption in buildings as well as in industries have been a field of intensive R&D in the 1970s at the period of the oil crisis and were abandoned soon after the crisis. Recently many activities related to the development of solar cooling applications were restarted. Henning [99] and Kim and Ferreira [100] have listed technical options from the solar radiation to the cooling effect: sorption (adsorption, absorption, desiccant), PV electricity (vapor compression) and thermo-mechanical option (Rankine, ejector, Stirling). In a solar thermo-mechanical refrigeration system, a heat engine converts solar heat into mechanical work, which in turn drives a mechanical vapour compression refrigeration machine. Heat engines such as Stirling engine, Brayton cycle and the Rankine engine can be used for this purpose. A schematic of such cooling system is shown in Fig. 9.

In a Duplex-Rankine cooling system, Rankine engine serves as heat engine and solar energy captured by solar collectors is turned into heat using a heat transfer fluid. This thermal energy is further transferred to the working fluid of the Rankine engine through the evaporator. The Rankine engine subsequently, transforms the heat received into mechanical power to drive the compressor of the vapor compression machine. The overall Coefficient of performance of the solar combined Rankine cooling system defined as the ratio of cold energy produced to the incident solar radiation is the product of the efficiencies of the solar collector, the Rankine power cycle and the cooling machine [100].

The literature review reveals little interest on this topic. Most activities on this technology were carried out in USA, Japan and Saoudi-Arabia in 1970s and 1980s and mainly theoretical investigations are reported. Lior [101] studied a solar-powered,

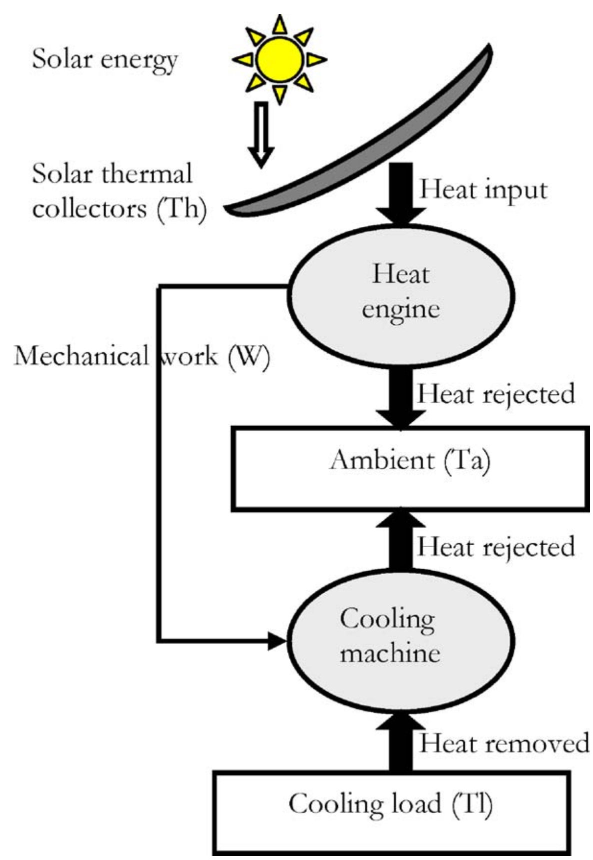

Fig. 9. Solar thermo-mechanical refrigeration system.

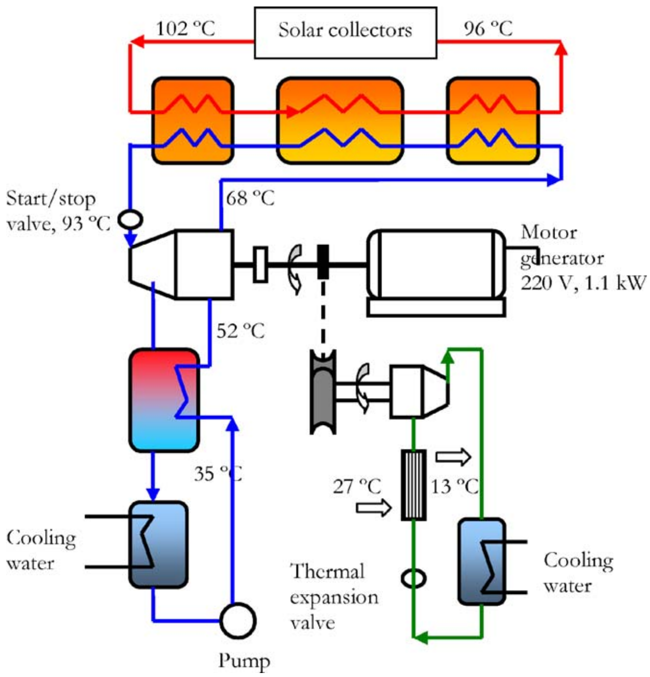

Fig. 10. Solar heated Rankine combined power/air conditioning system [102].

fuel-superheated Rankine cycle incorporating a steam turbine. A superheater is integrated into the system to avoid a two-phase operation of the turbine. This system was designed to work in cooling as well as in heating mode. Because of the economy-of-scale, this option would only be applicable for large refrigeration systems. For low-power systems and moderate temperature heat sources, design problems arise: excessive turbine shaft speed, high degree of superheat (~560 °C), turbine-blade erosion, etc. [14]. To overcome the design difficulties, organic fluids were suggested by Wali [14] who assessed different possibilities and proposed R113 as a suitable fluid.

A prototype of solar Rankine driven cooling system was designed and tested by Barber-Nichols Engineering Co., USA, in the framework of a project co-funded by Honeywell Inc. and the National science Foundation [102]. The demonstration package developed for supplying residential cooling and/or electricity via a solar heated Rankine cycle as depicted in Fig. 10, comprised a 3-ton air conditioning working with R12, 1-kW electric system, a R113 Rankine cycle, and a solar collector that provides warm water at 102 °C. With a turbine efficiency of 80% and a compressor efficiency of 85%, the coefficient of performance of the combined Rankine/air conditioning system is 0.71. The system thermal ratio or solar COP is 0.21, considering solar collector efficiency of 30%.

In the 1970s, Duplex-Rankine systems were considered for further competition with absorption but it was later abandoned. In such system, the prediction of component performance at off-design conditions and the matching of components into a complete system so that the overall performance is optimized are not easy. An adequate control strategy is needed to ensure matching the Rankine cycle and the air conditioner. Moreover, substances used as working fluids are harmful for the environment. A system-cost comparison carried by Kim and Ferreira [100] shows that duplex-Rankine with 2300 €/kWcool is cheaper compared with other thermo-mechanical systems but two to three-fold expensive in comparison to sorption options. For the abovementioned reasons, sorption systems utilizing environmentally friendly working media are preferred today.

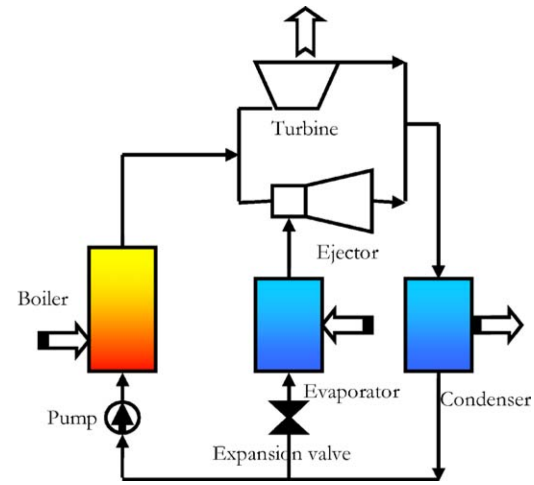

Fig. 11. The combined ejector/Rankine cycle [105].

A new path being explored is the combination of Rankine and ejector/absorption cycles for simultaneous production of cooling and power. A combined power and cooling cycle that combines Rankine and absorption refrigeration cycles and uses ammonia-water mixture was proposed by Goswami [103]. Wang et al. [104] proposed and performed thermodynamic analysis of a new combined cooling, heating and power (CCHP) system which combines Rankine and ejector refrigeration cycles. In their system, vapor extracted from the turbine supplies the ejector and the heat to users. Another combined Rankine/ejector system was designed, built and tested by Oliveira et al. [105]. As shown in Fig. 11, the ejector is mounted in parallel with the expander. Two prototypes were tested in Porto, Portugal and Loughborough, UK. The overall COP obtained was about 3.5% for a boiler temperature of 95 °C and ambient temperature of about 20 °C.

2.5. Ocean thermal energy conversion systems

The Earth's oceans cover over 70% of the planet and could be utilized as a source of virtually inexhaustible renewable energy. Ocean Thermal Energy Conversion (OTEC) by the way it employs natural thermal stratification occurring in oceans is being proposed to harness this huge amount of untapped energy, it converts solar radiation stored in the upper ocean water layers into electric power. Vertical ocean seawater temperature distribution has been measured in many regions around the world, and surface seawater at less than 50 m from sea level is warm at 20–29 °C while at a depth of about 800 or more the temperature is about 2–7 °C. To be effective, the minimum temperature difference between the ocean surface layers should be around 20 °C [106]. These temperature gradients are found in tropical regions near the Equator (Fig. 12).

The first known OTEC system was proposed by Arsene d'Arsonval, in 1881 [107]. He built a closed OTEC system with ammonia as working fluid. Ammonia was selected for its low boiling point as it could boil at low temperature. But the technology was never tested by d'Arsonval himself. George Claude overtook the challenge by proposing and successfully testing the open-cycle concept. Nevertheless, most of his attempts to put OTEC into practical use ended in failure. In 1962, H. Anderson and his son James H. Anderson Jr., began full scale design analysis of OTEC systems and conceived a new OTEC plant which overcame the weak points of Claude's system. Later, the energy crisis of 1973 provided the motivation for Japan and USA to perform fundamental research. Today, there are five different cycles known for OTEC. These are [107,108]: open OTEC cycle, closed OTEC cycle, hybrid OTEC cycle, Kalina cycle

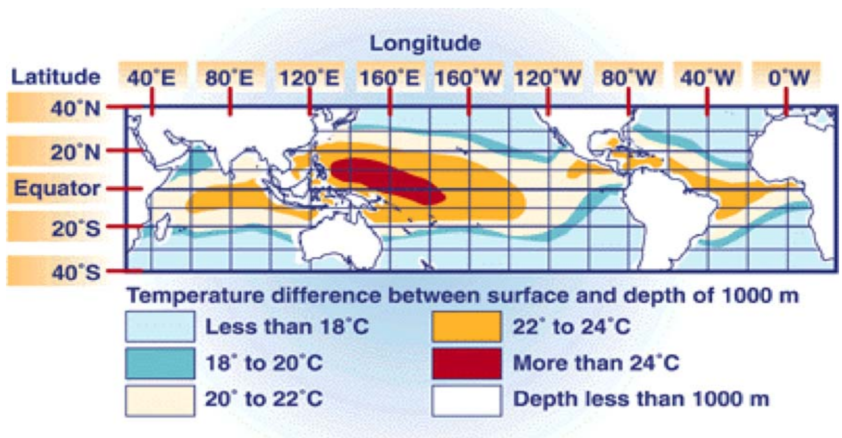

Fig. 12. Potential locations for OTEC plants [106,109].

and Uehara cycle. The closed cycle OTEC power plant concept was first proposed by D'Arsonval in 1881. It uses a working fluid with a low-boiling point, such as ammonia, propane or R134a and operates on a Rankine cycle. The working fluid is heated and vaporized in the evaporator by the warm surface seawater. The steam produced drives a turbine coupled to a generator. After the expansion process, the low-pressure working fluid vapor is condensed during a heat exchange with the cold seawater from the deep ocean. The working fluid is then pumped back to the evaporator and the cycle is repeated continuously. Fig. 13 shows a flow sheet diagram of a closed OTEC cycle [109].

An OTEC system utilizes very low grade energy and yields very low efficiency of about 3–5%. Therefore, generating high capacity power requires enormous quantity of seawater and pumping energy that could decrease the cost-effectiveness of this technology. It was proposed OTEC being integrated in a multiple industrial complex [110]. An Integrated Ocean Thermal Energy Conversion System (I-OTECS) apart from generating electricity could potentially tackle other ventures: fresh water production, air conditioning and refrigeration, cold water agriculture, aquaculture and mariculture, hydrogen production, lithium extraction, etc. Potential markets for OTEC have been identified, most of which are in Pacific Ocean and 50 countries are examining its implementation as alternative energy source and sustainable solution for water scarcity: India, Korea, Palau, Philippines, Hawaii, Papua New Guinea, etc. In 2001, as a result of cooperation between Japan and India a 1 MW plant was erected and many others are planned to be constructed in the near future. At the moment, this technology is gaining worldwide attention as one of the most reliable solution to most issues facing the world and many multi-purposes OTEC plants are expected to be built in the next future.

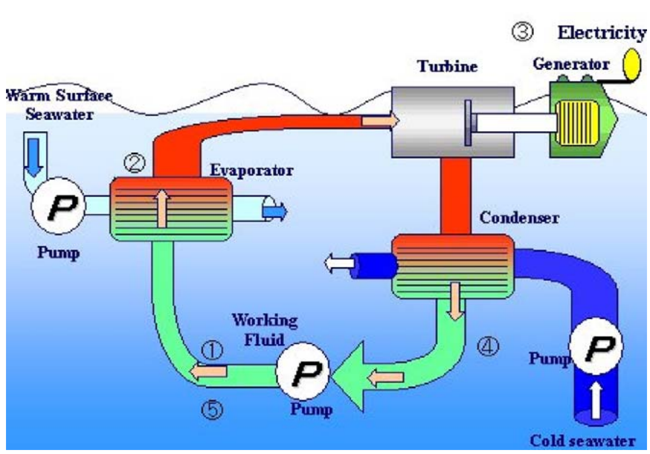

Fig. 13. Schematic of a closed OTEC [109].

2.6. Organic Rankine cycles (ORCs) in waste heat recovery application

Waste heat is the unused heat generated during a combustion process or any other chemical reaction/thermal process and, then directly exhausted to the environment. Industrial energy intensive processes as well as thermal engines and mechanical equipments produce large amounts of such waste heat [111–113]. Exhausts discharged do not only contain high exergy value but also large quantities of pollutants: carbon dioxide (CO_2), nitrogen oxides (NO_x) and surlphur oxides (SO_x) responsible of high level concentration of atmospheric greenhouse gases and of the global warming. Some developed countries in view of cutting off their harmful gas emissions while decreasing their energy imports in the meantime have evaluated their waste heat recovery potential. A study conducted within the eight largest manufacturing sectors in Canada showed up to 70% energy input lost [114]. According to a report published by the US Department of Energy (DOE) in 2008, the industrial sector alone accounts for about one third of the total energy consumed in the country and contributes in the same proportion to greenhouse gas emissions. The total heat lost amounts to about 20–50% of energy input, which could be partly recovered to reduce the country's energy intensity [115]. Processes requiring high energy demand are in the following sectors [112,115,116]: metal industry (Iron, Steel, Copper, Aluminum and Glass), Cement and building material industry, Food and beverage processing industry, Pulp and paper industry, Petroleum and Chemical industry.

Key parameters of waste heat streams are: stream matter state, mass flow rate, heat temperature, stream composition and availability. Liquid and solid streams, hot air and flue/process gases, pressurized hot water, wastewater and exhaust vapour are typical streams recorded[116]. Three categories of waste heat sources are distinguished with respect to the temperature level: low (<230 °C), medium (230–650 °C) and high (>650 °C). The heat source temperature is an essential parameter; it determines the efficiency of the energy recovery process and significantly impacts the heat exchangers design. Waste heat sites and thermal levels are listed in Table 5 [117].

A wide range of energy recovery technologies has been developed to make use of the large amounts of heat wasted. These include various types of heat exchangers (recuperators, regenerators, air preheaters, economizers, heat pipes, waste

Table 5
Waste heat sources and temperature range [115].

Categories	Heat sources	Temperature (°C)	Suggested recovery technology
High temperature (>650 °C)	Solid waste	650–1000	Air preheating
	Fume incinerators	650–1450	Steam Rankine cycle
	Nickel refining furnace	1370–1650	Steam generation (Heating)
	Glass melting furnace	1000–1550	Heat exchanger (preheating)
	Aluminum refining furnaces	650–760	Thermoelectric
	Copper reverberatory furnace	900–1100	Thermal PV
	Copper refining furnace	760–815	
	Zinc refining furnace	760–110	
	Cement kiln	620–730	
	Hydrogen plants	650–1000	
Medium temperature (230–650 °C)	Steam boiler exhaust	230–480	Steam Rankine cycle
	Gas turbine exhaust	370–540	Organic Rankine cycle
	Drying and baking ovens	230–600	Heat exchangers (pre–heating process)
	Catalytic crackers	425–650	Air pre-heating
	Reciprocating engine exhausts	315–600	Thermoelectric
	Drying and baking ovens	230–600	Thermal PV
	Catalytic crackers	425–650	
	Annealing furnace cooling systems	425–650	
Low temperature (<230 °C)	Process steam condensate	50–90	Space heating
	Cooling water from:		Domestic water heating
	Internal combustion engines	66–120	Heat pump
	Hot processed liquids and solids	32–232	Organic Rankine Cycle
	Annealing furnaces	66–230	Heat exchangers
	Drying, baking and curing ovens	93–230	Absorption/adsorption cooling
	Welding and injection molding machines	32–88	Kalina cycle
	Bearings	32–88	Piezoelectric
	Air compressors	27–50	

heat boilers, etc.), heat pumps, absorption/adsorption cooling machines and heat-to-electricity converters. Power generation from waste heat can be achieved using thermodynamic power cycles [114]: steam Rankine cycle, organic Rankine cycle, Kalina cycle, Goswami cycle, and transcritical/supercritical cycles or direct processes in [115]: thermoelectric, thermionic, and piezoelectric devices. Whereas heat driven power cycles are advanced or already mature, direct conversion techniques are still under development.

In general, conventional steam cycles operate in medium to high temperature and have gained in maturity since the 1970s, but cannot be cost-effective neither at smaller scale nor for low temperature resources [118]. In the low-to-medium temperature range organic Rankine cycles and Kalina cycles have demonstrated their ability to serve with advantage going to the first, which show less complexity. Heat transfer from the hot site to the power cycle can be executed by two ways [119]: (1) exhaust/process heat and working fluid streams exchange in the same heat exchanger or (2) a thermal oil loop is integrated to avoid risky contact between exhaust flows and flammable working fluid (Fig. 14). The choice of the ORC machine primarily depends on the heat source temperature and the desired power output[60]. As illustration, the tri-O-gen machine is designed for heat sources above 350 °C and produces up to 165 kW while PureCycle280 (Pratt & Whitney) produces up to 250 kW and is suitable for source temperature below 150 °C [120]. Although customized ORC modules can be ordered from suppliers, major difficulty resides in the optimal design and integration of the heat exchangers network aiming at maximizing the heat recovery efficiency. Selected systems are listed in Table 6. Features of ORCs in waste heat recovery application include but are not limited to the followings[121]:

- On-site power generation.
- Saving in power and additional income for the factory.
- Low O&M costs (no additional staff hired).
- No interference with operator's main tasks.
- Reduction in pollution (greenhouse gas emissions, thermal pollution).

This technology is progressively adopted for fuel efficiency and environmental protection in very different areas and processes where waste heat is available: power plants [19,122–125], manufacturing processes [126–128], cooling of technical equipment

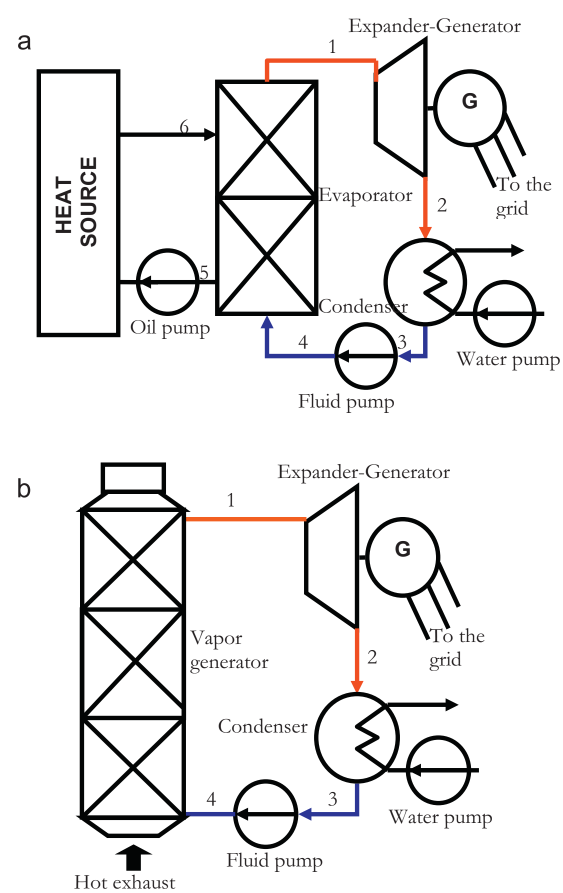

Fig. 14. Rankine cycles configurations in waste heat recovery application.

Table 6
Short list of ORC waste heat recovery plants.

Location	Waste heat generating system	Heat source type	Capacity	Technology	Start up
Mirom Roeselare, (Belgium), owner: Spie Belgium SA	Waste incinerator plant	Hot water at 180 °C	3 MW	Refrigerant/turboden	2008
Oxon Italia SPA, Pavia (I), Italy	8.3 MW MAN diesel engine	Exhaust gases	0.5 MW	Siloxane/turboden	2008
RHI, Radenthein (A), Austria	magnesite production process	Hot exhaust gas	0.8 MW	Siloxane/turboden	2009
Italcementi, Ait Baha (MA), Italy	Cement production process	Kiln exhaust gas	2 MW	Siloxane/turboden	2009
Gasseltenijveenschemond, Netherlands	2 × 646 kWe Jenbacher biogas engines	Exhaust	125 kW	ORC/tri-o-gen	
Nieuweroord, Netherlands	2 × 835 kW Jenbacher biogas engines	Exhaust	150 kW	ORC/tri-o-gen	
National Swimmingcentra The Tongelreep, Eindhoven, Netherlands	2.1 MW ABC Bio-oil engine	Exhaust	150 kW	ORC/tri-o-gen	
Savona, BC, Canada	Simple cycle gas turbine plant (18.5 MW)	Exhaust	4.5 MW	Pentane	2008
Kalamazoo Valley Community College, Michigan, USA	Boiler	exhaust		Twin-screw expander/Electratherm	2010
TransCanada pipeline, Gold Creek, Alberta, Canada	Gas Turbine (Rolls Royce, RB211/38000 HP)	Exhaust	6.5 MW	Ormat technology	1999
Northern Border Pipeline, St. Anthony, North Dakota	Gas Turbine (Rolls Royce, RB211/38000 HP)	Exhaust	5.5 MW	Ormat technology	2006
Northern Border Pipeline, Wetonka, South Dakota	Gas Turbine (Rolls Royce, RB211/38000 HP)	Exhaust	5.5 MW	Ormat technology	2007
Alliance Pipeline, Kerrobert, Saskatchenwan, Canada	Gas Turbine (GE LM2500/33000 hp)	Exhaust	5.5 MW	Ormat technology	2008
Northern Border Pipeline, Garvin, Minnesota	Gas Turbine (Rolls Royce, RB211/38000 HP)	Exhaust	5.5 MW	Ormat technology	2009
Northern Border Pipeline, CS 13, Minnesota	Gas Turbine (Rolls Royce, RB211/38000 HP)	Exhaust	5.5 MW	Ormat technology	2010
Kern River Pipeline, Goodsprings, Nevada	Gas Turbine (3 × Solar Mars 100/15000 HP)	Exhaust	6 MW	Ormat technology	2010
Spectra Pipeline, Australian, BC, Canada	Gas Turbine (GE PGT25+/31000 hp)	Exhaust	5 MW	Ormat technology	2010

[129], automotive industry [130,131], maritime transportations [132], etc. Three prospective areas are analyzed here below: the cement industry, the automotive industry, and the shipping industry.

Cement manufacturing process is very energy-intensive – the energy required for the production of a ton of cement is between 3 and 5 GJ/ton [133]. Fuelled by the economic growth experienced in developing countries, the cement production is steadily increasing. China alone produced about 1388 million metric tons (Mt) in 2008, which accounts for nearly half of the world's total cement production [134]. Cement manufacturing process is well known [133–135] and critical step is the clinker production that consumes about 80% of the total energy. Clinker is produced by burning a mixture of materials, mainly limestone, silicon oxides, aluminum, and iron oxides. The exit gases from the kilns are exhausted to the atmosphere at around 300–350 °C in 4 stages preheater and at 200–300 °C in case of 5–6 stages preheater. The clinker coming out of the kiln is at around 1000 °C and is cooled to 100–120 °C using ambient air. This generates hot air of about 200–300 °C. Hot air and gases exhausted to the environment can be recovered using well proven waste heat recovery steam technology pioneered by Japanese or by adopting low-temperature organic Rankine cycles [121]. Engin and Ari [136] conducted an energy audit of a typical cement factory with a capacity of 600 tons/day and showed that 40% of the total input energy was being lost through hot flue gas (19.15%), cooler stack (5.61%) and kiln shell (15.11%). By using a waste heat recovery steam cycle, low temperature heat from both hot air and flue gas streams could be recovered to produce on-site power of about 1 MW at a cost effective rate with a payback period of 17 months. Depending on the size of the plant, up to few tens of MW can be generated to cover 10–20% of the electricity needs and several plants have been installed worldwide, mainly in Japan, China and India. Organic Rankine cycles that offer greater modularity, lower investment and maintenance costs over steam cycles, could be a technology of choice for energy efficiency in cement industry.

In the 1970s and 1980s during the oil crisis, car manufacturers were concerned about reducing fuel consumption. But just after the oil shocks, the idea was left aside. However, in recent years, with new regulations on greenhouse gas emissions entering into force, the interest of reducing the fuel consumption and CO_2 emissions in cars is renewed. In current cars, the combustion engine onboard requires a supply of fuel three times as great as the power actually generated. This is because the combustion engine with its maximum efficiency of about 40% converts less than one third of the energy it receives into mechanical power [137]. For illustration, the heat balance of a typical 1.4 liters spark ignition engine has a thermal efficiency ranging from 15 to 32% depending on operating conditions. The remaining 60–70% of the energy input is rejected to the environment through the radiator (18–42%) and the exhaust system (22–46%) [130]. Rankine cycles are regarded as promising solution to recover this heat lost for thermal comfort or power generation. Several encouraging trials have been reported with steam as working fluid. Honda [131] designed and tested a prototype. The thermal efficiency of the latter improved from 28.9% to 32.7% when tested at a constant speed of 100 km/h. Organic Rankine cycles could provide substantial fuel saving by recovering not only the heat from exhausts but also that of the cooling circuit.

Several paths are under investigation in view of improving fuel efficiency in ships; the waste heat recovery being part of the R&D [138]. A conventional diesel engine converts about 30–50% of the energy of the bunker fuel into mechanical work for the ship's propulsion system and the remaining part is lost in the form of waste heat through the cooling system and the exhaust. Rankine cycles could recover part of the heat exhausted and turn it into additional power for onboard services, and/or to supplement the propeller. However, research papers on waste heat recovery on ships are scarce in literature. This could be explained by the lit-

Table 7
Classification of fluids in subcritical operations.

Low-temperature (LT) (<150 °C)		Medium-temperature (MT) (150–250 °C)		High-temperature (HT) (>250 °C)	
Fluids	T_{crit} (°C)	Fluids	T_{crit} (°C)	Fluids	T_{crit} (°C)
R32	78.11	RE347	160.2	N-Heptane	267.0
Propane	96.68	HFE7000	164.46	Cyclohexane	280.5
R134a	101.1	Novec649	168.66	Benzene	288.9
R245	107	SES36	177.5	Octamethyltrisiloxane (MDM)	291.1
R152a	113.3	R123	183.7	N-Octane	296.2
Ammonia	132.3	HFE7100	195.3	Toluene	318.6
i-Butane	134.8	Hexane	234.6	Decamethyltetrasiloxane (MD2M)	325.8
R236ea	139.29	N-Pentane	196.5	Dibromomethane (R-30B2)	337.8
RE-134	147	Methanol	240.2	N-Propylbenzene	365
n-Butane	152.3	Ethanol	240.8	N-Butylbenzene	388
R25fa	154.1	Hexamethyldisiloxane (MM)	245.4	Tribromomethane (R-20B3)	422.9

tle interest shown till recent years by the shipping industry to cut off greenhouse gases emitted and/or the competition within shipping industry which prevents the companies from releasing information related to their R&D. Nevertheless, few works available can be quoted. Tien et al. [132] performed a parametric study of a steam cycle used as bottoming cycle on a ship. They concluded that exhaust heat characteristics, mainly mass flow rate, exhaust inlet and outlet temperature are critical parameters which influence significantly the performance of the bottoming cycle. Schmid [139] reported findings of a joint R&D project headed by Odense Steel Shipyard Ltd in cooperation with Wartsila Corp., Siemens AG, Peter Brotherhood Ltd and Aalborg Industries Ltd. The engine investigated was a Sulzer 12RT-flex96C model. The engine efficiency was about 49.3% and the rest of energy was exhausted to the environment via different streams: exhaust gas (25.4%), scavenge air cooling water (14.1%), jacket water (6.3%) and lubricating oil (4.3%). Provided a well integrated heat recovery system is used, the efficiency could increase by 12% and save up to 10 tons of bunker fuels per day. Opcon, a Swedish energy technology group, recently announced it will install an Organic Rankine Cycle module on a ship [140]. The installation aims at achieving 4–6% fuel savings which translated into emissions means a cut in carbon dioxide and sulphur dioxide emissions of about 37,000 and 150 tons a year, respectively.

Organic Rankine cycle with the capability it has to convert unused low temperature resources into electricity has become an important topic in power engineering and the number of published papers is rapidly increasing. Various aspects are addressed, but most of time, studies focus on working fluids and cycle optimal design [8,9,12,15,48,124,141–157]. From the abundant relevant literature, following remarks can be extracted:

- Based on the critical temperature which limits the evaporation temperature in subcritical cycles, fluids can be grouped in three categories as displayed in Table 7:
  - High temperature fluids (HT: $T_{crit} > 250\,°C$)
  - Medium temperature fluids (MT: $150 < T_{crit} < 250\,°C$)
  - Low temperature fluids (LT: $T_{crit} < 150\,°C$):
- Fluid mixtures:
  - best matching with exhaust stream
  - additional choice for fluids
  - suitable for cogeneration
  - difficult to implement
  - no practical experience
- transcritical/supercritical operations:
  - best match with exhaust stream
  - better efficiency and higher power output
  - excessive pressure in the evaporator
  - no practical experience

An important problem encountered with waste heat ORCs is the transient conditions due to fluctuations of the heat parameters and load demand which may be detrimental to the system: stalling or temperature shocks. Appropriate control and monitoring systems are thus required to keep the proportion of liquid and vapour phases in the condenser and evaporator within acceptable ranges. Only a limited number of authors have provided insight look at this issue: Wei et al. [158] and Quoilin et al. [159] proposed dynamic models of ORCs using turbine and scroll expander, respectively.

Capital costs and profitability of ORC waste heat recovery installations are strongly site and application dependent. Quality and quantity of available heat determine the choice of the suitable machine and type of heat recovery exchangers. The cost of high temperature ORCs based on turbine technology varies from 1000 €/kW for MW-size up to 3000 €/kW for a hundred kW power unit[120]. Assuming an installation cost 50% that of the ORC engine, the total specific investment cost amounts to about 1500–4500 €/kW. Schuster et al. [19] reported an electricity production cost (epc) of 5.65 c€/kWh for a case study of a biogas plant where an ORC produced 35 kWe power from exhaust heat recovered. Economic profitability of a 2 kW unit using scroll expander was evaluated by authors who obtained a levelized electricity cost (LEC) of 13 c€/kWh [160]. Intense R&D and subsidies or other financial scheme such as feed-in-tariff were identified as necessary conditions for wide adoption of waste heat recover ORCs.

2.7. ORC biomass power plants

Biomass is the world's fourth largest energy source, contributing to nearly 10% of the world's primary energy demand [161]. In developing countries, the contribution of biomass to the national primary energy demand is higher, up to 70–90% in some countries and usually used in unsustainable way [162]. This abundant resource could be transformed into electricity and heat when necessary in CHP plants. Various potential technologies that could serve this purpose were listed by Dong et al. [163].

The ORC binary biomass technology is receiving an increasing attention for application in small scale distributed electricity generation. A typical system is made up of a biomass feed-boiler and an Organic Rankine Cycle module coupled via a thermal oil loop (Fig. 15). Biomass fuel is burned through a process close to that used conventional steam boilers. The thermal oil used as heat transfer medium provides a number of advantages, including low pressure in the boiler, large inertia and insensitivity to load changes, simple and safe control and operation. Moreover, the adopted hot side temperature (below 350 °C) ensures a long oil life. The heat carried by the thermal oil is transferred to the organic Rankine cycle and converted into electricity. Well selected organic fluids such as octamethyltrisiloxanes (OMTS) and alkylbenzenes insure the opti-

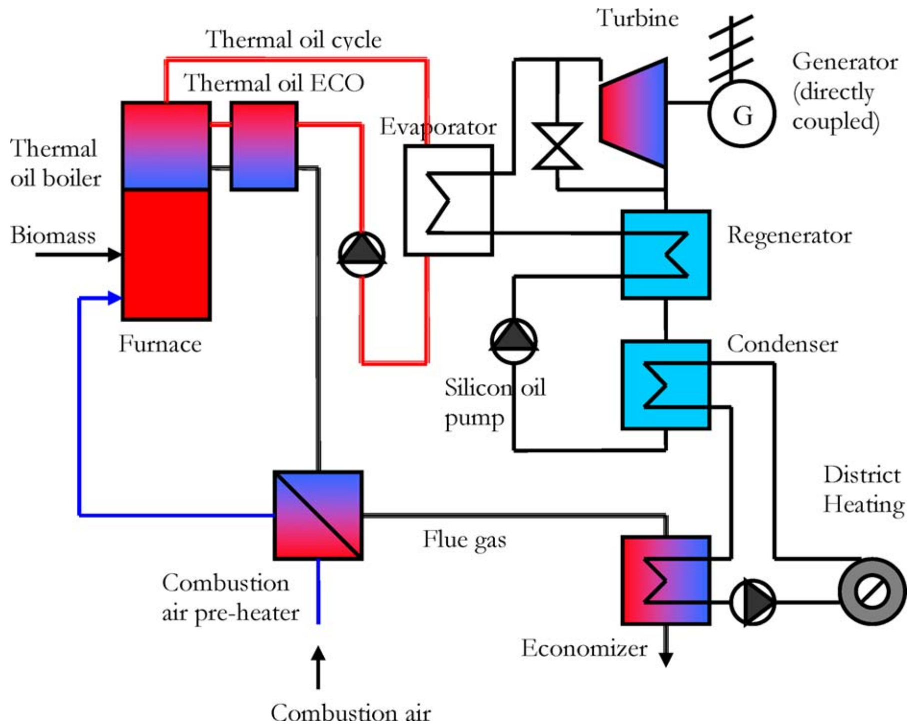

Fig. 15. Schematic of a biomass power plant [165].

mal operation of the cycle as shown by Drescher and Bruggemann [164]. The condensation heat is used to produce hot water at a temperature between 80 and 120 °C suitable for district heating and other thermal processes such as wood drying and sorption cooling.

Biomass ORC CHP plants at medium scale (100–1500 kW) have been successfully demonstrated and are now commercially available [19] while small scale systems of few kW are still under development. The number of installed plants is rapidly increasing as the technology is becoming mature and cost effective. Till now, most of installations are in Europe, and Stadtwarme Lienz Austria (1000 kWe), Sauerlach Bavaria (700 kWe), Toblach South Tyrol (1100 kWe), and Fuβach Austria (1500 kWe) are just few of them.

Although at least a hundred plants have been installed throughout the world, technical data on existing plants are very scarce. Evaluations reports were released for two demonstration plants in Austria [165,166]: Admont CHP plant (400 kWe) and Lienz (1000 kWe). The biomass CHP plant in Lienz supplies the town of Lienz with district heat (60,000 MWh/year) and feeds the electricity produced (7200 MWh/year) into the grid. The plant was fully automatic, and presented excellent part load operation with and electrical efficiency of 18%. The overall plant efficiency amounts to 82%. Specific installation cost was estimated at about 2765 €/kWe and electricity production costs in the range 9–14 c€/kWhe depending on the fuel price and capacity utilization.

3. Conclusion

The paper presented a review of organic Rankine cycle applications. These applications include solar thermal electricity, solar thermal driven reverse osmosis desalination (Solar ORC-RO), Duplex-Rankine cooling, solar pond power systems, ocean thermal energy conversion (OTEC), biomass combined heat and power plants (CHP), binary geothermal systems and low-grade waste heat recycling (ORC-WHR) from thermal devices and processes. Rankine cooling systems are almost abandoned with preference to sorption cooling systems which require less moving parts and use more environmentally friendly substances. Solar ORC-RO is still at the research stage. Modular solar thermal and solar pond power plants although proven, are not yet widely adopted. OTEC is intensely investigated as future major technology for isolated islands with favorable seawater thermodynamic characteristics. Biomass and binary geothermal CHP are already mature. ORC-WHR is the fastest growing business among ORC solutions, with great potential in industry and combined cycle power plants. Environmental concern over climate change and rising oil prices are reasons supporting the explosive growth of this efficient, clean and reliable way of producing electricity.

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